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Inferential Control Strategy for Chemical Distillation Process Based on Gray Image Encryption Recognition Algorithm

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In view of the problem that it is impossible to detect the product components online during the chemical rectification process and the low control precision of the conventional control strategy in which the product components are controlled indirectly by temperature, under the premise that the object model is unknown, the gray image encryption recognition algorithm (hereinafter referred to as GIERA for short) is used to study the inferential control strategy for chemical distillation process (hereinafter referred to as ICSCDP for short) in this paper. Aiming at the characteristic of the presence of coupling in the chemical distillation process, the hyperchaotic encrypted image algorithm is used to implement the inferential control of the chemical distillation process. Subsequently, the active disturbance rejection controller (hereinafter referred to as ADRC for short) is designed for the time delay subsystems after the inferential control is carried out. In the simulation experiment, the Wood-Berry model is taken as an example to verify the effectiveness of the algorithm put forward in this paper.

1. Introduction

Chemical production is a kind of ubiquitous, coupled, time delay process objects with multi input and multi output. In the chemical process control, anti-interference control or steady state adjustment is often carried out near the actual working point. Therefore, it is necessary to carry out linearization near the working point to obtain the transfer function matrix of the system. In the inferential control of the industrial sites, the step response or frequency response of the system is obtained by the application of the step signal or the sinusoidal signal at different frequency (Ma et al., 2013). After the response curve is obtained, the transfer function of the system can be solved by using the graphical method. Such kind of method has been widely used in the industrial sites (Gil et al., 2012). However, if the system response thus obtained is mixed with a lot of noise, the calculation accuracy of the graphical method will be subject to great limit [10]. A kind of improved frequency response test experiment is carried out. In this experiment, the asymmetric rectangular signals are used to obtain the information at the important frequency, which has implemented the inferential control of the chemical distillation process in the noisy environments (Du et al., 2014). In the inferential control method of the first-order time delay systems under the step response, the integral equation of the system is transformed into the model for solving the inferential control problem based on the hyperchaotic encrypted image algorithm by obtaining the integral of the step response. On this basis, the inferential control method under the step response of the n-order time delay systems is obtained (Lin et al., 2014). In recent years, the inferential control methods for the inferential control system of the chemical distillation process such as the successive approximation method, the subspace method and so on has been widely used in the chemical process control. However, there are still many problems in the inferential control of the multivariable time delay systems, and further research is required to solve these problems (Meidanshahi and Adams, 2016).

2. Inferential control of the chemical distillation process

The Wood-Berry (WB)model of the chemical distillation column is shown in the equation (1) and the equation (2). It can be seen that the inferential control of the chemical distillation process is composed of the first-order and the second-order time delay transfer functions (Azelan et al., 2018). The method for the inferential control

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based on the step response model in the study of the first-order and the second-order time delay objects in this paper as the following.

$$G_{WB}(s)=\begin{bmatrix}\frac{12.8e^{-s}}{16.7s+1} & \frac{-18.9e^{-3s}}{21s+1}\\ \frac{6.6e^{-7s}}{10.9s+1} & \frac{-19.4e^{-3s}}{14.4s+1}\end{bmatrix} \tag{1}$$

$$G_{OR}(s)=\begin{bmatrix}\frac{0.66e^{-2.6s}}{6.7s+1} & \frac{-0.61e^{-3.5s}}{8.64s+1} & \frac{0.0049e^{-1s}}{9.06s+1}\\ \frac{1.11e^{-6.5s}}{3.25s+1} & \frac{-2.36e^{-3s}}{5s+1} & \frac{-0.01e^{-1.2s}}{7.09s+1}\\ \frac{-34.68e^{-9.2s}}{8.15s+1} & \frac{46.2e^{-9.4s}}{10.9s+1} & \frac{0.87(11.61s+1)e^{-s}}{(3.89s+1)(18.8s+1)}\end{bmatrix} \tag{2}$$

2.1 Inferential control of the first-order time delay system

It is assumed that the transfer function of the first-order delay system is as shown in the equation (3) as the following:

$$G(s)=\frac{K}{Ts+1}e^{-\tau s} \tag{3}$$

Under the unit step response, the output y (s)of the system can be expressed as the following:

$$y(s)=G(s)u(s)=K\left(\frac{1}{s}-\frac{1}{s+\lambda}\right)e^{-\tau s} \tag{4}$$

In which: λ=1/T. In the case that there is the presence of the white noise interference, the output response y (t)of the system can be expressed as the following:

$$y(t)=\begin{cases}n(t), & t\rangle\tau\\ K\left(1-e^{-\lambda(t-\tau)}\right)+n(t) & t\ge\tau\end{cases} \tag{5}$$

From the equation (5), it can be known that: K=y(∞)-n(∞). The value for the parameter K can be calculated by averaging a segment of data when the system reaches the steady state.
It is assumed that Δy(t)=y(t)-K, then the following can be obtained:

$$e^{-\lambda(t-\tau)}=-\frac{\Delta y(t)}{K}+\frac{n(t)}{K},\ t\ge\tau \tag{6}$$

Let $t_1>\tau$, then the integral in the interval $[0, t_1]$ be expressed as the following:

$$\int_0^{t_1}\Delta y(t)dt=-K\cdot\tau+K\cdot\frac{e^{-\lambda(t-\tau)}}{\lambda}\Big|_{\tau}^{t_1}+\int_0^{t_1}n(t)dt \tag{7}$$

The equation (6) is introduced into the equation (7), and the following can be obtained:

$$\int_0^{t_1}\Delta y(t)dt=-K\cdot\tau-\frac{\Delta y(t_1)}{\lambda}-\frac{K}{\lambda}+\frac{n(t)}{\lambda}\Big|_{\tau}^{t_1}+\int_0^{t_1}n(t)dt \tag{8}$$

Let $\delta(t_1)=\frac{n(t)}{\lambda}\Big|_{\tau}^{t_1}+\int_0^{t_1}n(t)dt$, $\phi=\left[-K\ -\Delta y(t_1)\right]$, $\theta=\left[\tau+1/\lambda\ \ 1/\lambda\right]^T$, $\gamma(t_1)\int_0^{t_1}\Delta y(t)dt$, then the equation (8)can be expressed as the following:

$$\phi\cdot\theta=\gamma(t_1)+\delta(t_1) \tag{9}$$

Through the equation (9), the parameter of the system can be obtained through the inferential control based on the hyperchaotic encrypted image algorithm. The step response of the system is sampled. It is assumed that the sampling time is T_s, then the data from the m-th sampling point to the (m+n)'s sampling point is extracted, which can be expressed with the matrix equation form as the following:

$$\Phi\theta=\Gamma+\Delta \tag{10}$$

In which: $\Phi = \begin{bmatrix} -K & -\Delta y[mT_s] \\ -K & -\Delta y[(m+1)T_s] \\ \vdots & \vdots \\ -K & -\Delta y[(m+n)T_s] \end{bmatrix}$, $\Gamma = \begin{bmatrix} \gamma[mT_s] \\ \gamma[(m+1)T_s] \\ \vdots \\ \gamma[(m+n)T_s] \end{bmatrix}$, $\Delta = \begin{bmatrix} \delta[mT_s] \\ \delta[(m+1)T_s] \\ \vdots \\ \delta[(m+n)T_s] \end{bmatrix}$.

The hyperchaotic encrypted image algorithm is used, and the estimated value for the parameter θ can be obtained as the following:

$$\hat{\theta} = \left(\Phi^T \Phi\right)^{-1} \Phi^T \Gamma \tag{11}$$

Taking the integral term that contains the noise in Δ into consideration, the hyperchaotic encrypted image algorithm will produce a biased estimate. At this point, the auxiliary variable method is used to improve the accuracy of the inferential control, and the auxiliary variable ∏ is selected as the following:

$$\prod = \begin{bmatrix} mT_s & \frac{1}{mT_s} \\ (m+1)T_s & \frac{1}{(m+1)T_s} \\ \vdots & \vdots \\ (m+n)T_s & \frac{1}{(m+n)T_s} \end{bmatrix} \tag{12}$$

The estimated value taken for the parameter θ in the equation (9) by using the auxiliary variable hyperchaotic encrypted image algorithm can be expressed as the following:

$$\hat{\theta} = \left(\prod^T \Phi\right)^{-1} \prod^T \Gamma \tag{13}$$

2.2 Inferential control of the second-order time delay system

The inferential control process of the second-order time delay systems is similar to the that of the first-order time delay. At this point, it is assumed that the transfer function of the system is as the following:

$$G(s) = \frac{a_1 s + a_2}{s^2 + b_1 s + b_2} e^{-\tau s} \tag{14}$$

Under the unit step response, the output y (s)of the system can be expressed as the following:

$$y(s) = \frac{a_1 s + a_2}{s^2 + b_1 s + b_2} \cdot \frac{1}{s} \cdot e^{-\tau s} = \left(\frac{\beta_1}{s} + \frac{\beta_2}{s+\lambda_1} + \frac{\beta_3}{s+\lambda_2}\right) e^{-\tau s} \tag{15}$$

In which: $\beta_1 = \frac{a_2}{\lambda_1 \lambda_2}$, $\beta_2 = \frac{-a_1\lambda_1 + a_2}{-\lambda_1(-\lambda_1+\lambda_2)}$, $\beta_3 = \frac{-a_2\lambda_2 + a_2}{-\lambda_2(-\lambda_2+\lambda_1)}$. *$\lambda_1$* and *$\lambda_2$* stand for two poles of the second-order system. It is assumed that *$\lambda_1 \neq \lambda_2$*, then the output response y (t)of the system can be expressed as the following:

$$y(t) = \begin{cases} 0, & t < \tau \\ \beta_1 + \beta_2 e^{-\lambda_1(t-\tau)} + \beta_3 e^{-\lambda_2(t-\tau)}, & t \geq \tau \end{cases} \tag{16}$$

From the equation (16), it can be known that: *β_1*=*y*(∞)-*n*(∞). By taking the mean value of a segment of data when the system reaches the steady state, the value for the parameter *β_1* can be obtained through calculation. It is assumed that Δy(t)=y(t)- ***β_1*,** *t_1*>τ, Δy(t) one time integrator and double integrator in the interval [0, t] can be expressed as the following:

$$\int_0^t \Delta y(t_1)\,dt_1 = -\beta_1\tau - \frac{\beta_2}{\lambda_1} e^{-\lambda_1(t-\tau)} - \frac{\beta_3}{\lambda_2} e^{-\lambda_2(t-\tau)} + \frac{\beta_2}{\lambda_1} + \frac{\beta_3}{\lambda_2} \tag{17}$$

$$\int_0^t \int_0^{t_2} \Delta y(t_1)\,dt_1 dt_2 = \frac{1}{2}\beta_1\tau^2 - \beta_1\tau t + \frac{\beta_2}{\lambda_1^2} e^{-\lambda_1(t-\tau)} - \frac{\beta_3}{\lambda_2^2} e^{-\lambda_2(t-\tau)} - \frac{\beta_2}{\lambda_1^2} - \frac{\beta_3}{\lambda_2^2} + \left(\frac{\beta_2}{\lambda_1} - \frac{\beta_3}{\lambda_2}\right)(t-\tau) \tag{18}$$

Through the equation (16) and the equation (17), the following can be obtained:

$$\beta_2 e^{-\lambda_1(t-\tau)} = \frac{\lambda_1}{\lambda_1-\lambda_2}\Delta y(t) + \frac{\lambda_1\lambda_2}{\lambda_1-\lambda_2}\times\left(\int_0^t \Delta y(t_1)\,dt_1 + \beta_1\tau - \frac{\beta_2}{\lambda_1} - \frac{\beta_3}{\lambda_2}\right) \tag{19}$$

$$\beta_3 e^{-\lambda_2(t-\tau)} = \frac{-\lambda_2}{\lambda_1-\lambda_2}\Delta y(t) - \frac{\lambda_1\lambda_2}{\lambda_1-\lambda_2}\times\left(\int_0^t \Delta y(t_1)\,dt_1 + \beta_1\tau - \frac{\beta_2}{\lambda_1} - \frac{\beta_3}{\lambda_2}\right) \tag{20}$$

The equation (19) and the equation (20) are introduced into the equation (18), and the following can be obtained:

$$\int_0^t\int_0^{t_2} \Delta y(t_1)\,dt_1 dt_2 = \frac{1}{\lambda_1\lambda_2}\Delta y(t) - \left(\frac{1}{\lambda_1}+\frac{1}{\lambda_2}\right)\int_0^t \Delta y(t_1)\,dt_1 - \left(\frac{1}{\lambda_1\lambda_2} + \frac{a_1}{a_2}\tau - \frac{1}{2}\tau^2\right)\beta_1 - \left(\frac{1}{\lambda_1}+\frac{1}{\lambda_2}+\tau-\frac{a_1}{a_2}\right)\beta_1 t \tag{21}$$

3. Inferential design of the chemical distillation process based on the gray image encryption recognition algorithm

GIERA has been widely used in the inferential control of the chemical distillation process, and good control effect has been achieved. After the hyperchaotic encrypted image algorithm is used, the inferential control system of the chemical distillation process that is originally coupled seriously has become a diagonal transfer function matrix. In this way, the active disturbance rejection controller can be designed for each channel respectively to implement the inferential control of the original system. From the observation of the Wood-Berry model, it can be found that the majority of the transfer functions on the diagonal are first-order time delay systems. At this point, the transfer function (3) for the first-order time delay system can be rewritten into the time domain form as the following:

$$\dot{y}(t) = \frac{1}{T}y(t) + \frac{K}{T}u(t-\tau) + w(t-\tau) = f + b_0 u(t-\tau) \tag{25}$$

In which: w(t-τ) stands for the external disturbance of the system, b_0 stands for the estimated value of K/T, $f = -\frac{1}{T}y(t) + w(t-\tau) + (b-b_0)u(t-\tau)$ stands for the total disturbance, which is the sum of the internal uncertainty of the system and the external disturbance. The core idea of GIERA is to observe the total disturbance f of the system through the inferential control system. At this point, the total disturbance is regarded as the expanded state x_2 of the system. Then the equation (26) can be expressed by the state space equation as the following:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}b_0\\ 0\end{bmatrix}u(t-\tau) + \begin{bmatrix}0\\ 1\end{bmatrix}\dot{f} \tag{26}$$

$$\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix} = \begin{bmatrix}-2w_0 & 1\\ -w_0^2 & 0\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix} + \begin{bmatrix}b_0 & 2w_0\\ 0 & w_0^2\end{bmatrix}\begin{bmatrix}u(t)\\ y(t)\end{bmatrix} \tag{27}$$

In which: z_1 and z_2 stand for the observed values of the original system state x_1 and x_2, and w_0 is referred to as the bandwidth of the observer.

When certain conditions are met, the results of the theoretical analysis show that the aforementioned GIERA is closed-loop and stable. Taking into consideration the presence of the time lag of the system, the bandwidth w_0 of the observer (28) will be affected by the time lag, thus affecting the observation effect of the total disturbance. The following changes are carried out on the equation (28), and the time delay link is introduced at the input u (t), so that u (t)and y (t)can match each other in the time sequence. In this way, the system will obtain even greater bandwidth. In addition, the maximum time lag time that the system can tolerate is provided as the following.

$$\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix} = \begin{bmatrix}-2w_0 & 1\\ -w_0^2 & 0\end{bmatrix}\begin{bmatrix}z_1\\ z_2\end{bmatrix} + \begin{bmatrix}b_0 & 2w_0\\ 0 & w_0^2\end{bmatrix}\begin{bmatrix}u(t-\tau)\\ y(t)\end{bmatrix} \tag{28}$$

After the observed value z_2 of the total disturbance of the system is obtained, the control signals of the system can be designed as the following:

$$u = \frac{u_0 - z_2}{b_0} \tag{29}$$

The equation (29) is introduced into the equation (25), and the following can be obtained:

$$\dot{y} = f + b_0\left(\frac{u_0 - z_2}{b_0}\right) \approx u_0 \tag{30}$$

From the equation (30), it can be seen that through the compensation for the disturbance, there is approximately an integrator link between the input u $_0$ and the output y, and the control of the system can be achieved through a proportional controller as the following:

$$u_0 = k_p\left(r - y\right) \tag{31}$$

4. Simulation experiment

The gray image encryption recognition algorithm put forward in this paper is verified to test the effectiveness of the method described in this paper. The proposed algorithm is then compared with the traditional methods. In the experimental simulation, chemical distillation image with the size of 256 × 256 is used as the plaintext image, as shown in Figure 2, and the control parameters of the chemical distillation process inferential control system are determined by the characteristics of the image itself. The encrypted image obtained through the experiment is shown in Figure 3 as the following, and it can be seen that the encryption effect is good.

Figure 2. Plaintext diagram of the chemical distillation equipment

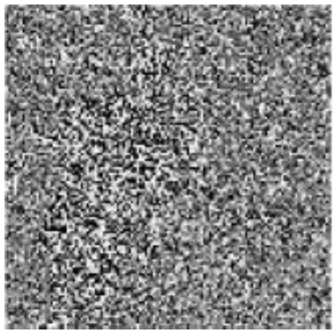

Figure 3. Encrypted image

The input and output data of the chemical distillation process inferential control system is obtained by the gray image encryption recognition algorithm, and the encrypted image algorithm is added to the output data. The plaintext sensitivity (hereinafter referred to as PS for short) is defined in accordance with the equation as the following:

$$NSR = \frac{mean\left(abs\left(noise\right)\right)}{max\left(abs\left(signal\right)\right)} \times 100\% \tag{32}$$

The result of the inferential control is checked by the mean square error as the following:

$$E = \frac{1}{N}\sum_{k=1}^{N}\left[y\left(kT_s\right) - \hat{y}\left(kT_s\right)\right]^2 \tag{33}$$

The result of the inferential control obtained in the environment when NSR=1% is as the following:

$$G_{WB}\left(s\right) = \begin{bmatrix} \dfrac{12.79e^{-1.01s}}{16.62s+1} & \dfrac{-18.91e^{-3.00s}}{20.99s+1} \\ \dfrac{6.6e^{-7.00s}}{10.86s+1} & \dfrac{-19.40e^{-3.00s}}{14.42s+1} \end{bmatrix}$$

The result of the inferential control obtained in the environment when NSR=10% is as the following:

$$G_{WB}(s)=\begin{bmatrix} \frac{12.81e^{-1.04s}}{16.70s+1} & \frac{-18.81e^{-3.08s}}{20.77s+1} \\ \frac{6.65e^{-6.95s}}{11.10s+1} & \frac{-19.34e^{-2.92s}}{14.42s+1} \end{bmatrix} \quad (34)$$

The mean square error E of each subsystem inferential control model and the actual model is shown in Table 1 as the following.

Table 1: *Mean square error of the inferential control results of the Wood-Berry model*

	G_{11}	G_{12}	G_{21}	G_{22}
NSR=1%	1.93×10^{-4}	6.37×10^{-5}	2.98×10^{-5}	4.69×10^{-5}
NSR=10%	4.88×10^{-5}	6.32×10^{-4}	6.62×10^{-4}	2.10×10^{-3}

5. Conclusions

In this paper, the inferential control of the chemical distillation process is taken as an example. The relevant characteristics of the plaintext image are used in the encryption process to generate the control parameters of the required gray image recognition system, so that the key sequence can be closely related to the plaintext image. When minor changes occur in the plaintext image, significant change will occur in the key sequence accordingly. Secondly, in the encryption process of the algorithm put forward in this paper, the internal pixel scrambling is carried out on each pixel and then the pixel diffusion operation is performed, so that the ciphertext is diffused and enhanced very well. In this way, the anti-differential attack capability of the encryption algorithm can be enhanced. Finally, through the simulation experiment, the effectiveness of the method put forward in this paper is verified.

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